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Near-extreme system condition and near-extreme remaining useful time for a group of products

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ABSTRACT

When a group of identical products is operating in field, the aggregation of failures is a catastrophe to engineers and customers who strive to develop reliable and safe products. In order to avoid a swarm of failures in a short time, it is essential to measure the degree of dispersion from different failure times in a group of products to the first failure time. This phenomenon is relevant to the crowding of system conditions near the worst one among a group of products. The group size in this paper represents a finite number of products, instead of infinite number or a single product. We evaluate the reliability of the product fleet from two aspects. First, we define near-extreme system condition and near-extreme failure time for offline solutions, which means no online observations. Second, we apply them to a continuous degradation system that breaks down when it reaches a soft failure threshold. By using particle filtering in the framework of prognostics and health management for a group of products, we aim to estimate near-extreme system condition and further predict the remaining useful life (RUL) using online solutions. Numerical examples are provided to demonstrate the effectiveness of the proposed method.

1. Introduction

Obviously if product reliability condition can be precisely monitored and predicted, there would be a significant reduction of catastrophic failures. According to our literatures for infinite numbers of products, reliability engineers focus on the mean time-to-failure and other statistically average assessment of product quality. Particularly for one product, prognostics and health management (PHM) technology enables health monitoring and failure prediction. Therefore, there is a gap between “infinite samples” and “one sample”, which is the “finite samples” for a group of products. These previous reliability indexes are good but are not sufficient to provide specific guidance for reliability prediction of a group of products. In this way, near-extreme issues are of great interest to evaluate for a group of products.

On one hand, the degree of system degradation condition near the worst condition is an important issue to evaluate whether there will be an aggregation of system degradation conditions or not. In other words, when we find the worst degradation condition among N products, are the most conditions of different products far away from the extreme condition, or close to the extreme condition? Near-extreme system condition contains two situations. One is that all products operate normally, and the other is that a failure occurs when the degradation reaches a predetermined failure threshold. On the other hand, we need to quantitatively describe and assess the crowding of near-extreme failure time for N products, in order to determine whether there will be a burst of failures or not. It should be noted that the degree of dispersion is measured from the first failure time among N products that is a variable, while the traditional mean time-to-failure is a constant value for infinite number of products. In addition, the reference for the near-extreme condition is probabilistic. Therefore, it is important to investigate both issues at the same time, namely the near-extreme condition and the near-extreme remaining useful life (RUL).

Extreme events leading to engineering failures often cause tremendous financial loss even casualties. What makes them even worse is that these near-extreme events will make a series of failures into disasters for companies and customers, which comes into notice for scientist and engineers. The maintenance strategy of infrastructure is optimized with deterioration for extreme events [1]. The extreme statistics was applied in physics [2], dynamic reliability analysis [3], time series for signals [4], structural health monitoring [5], hydrology [6]. The density of states near the extreme was computed by

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Notation

H	Soft failure threshold
N	The number of products
$X_i(t)$	System condition for the ith product at time t
$X_{\max}$	The worst degradation condition among N products
$p(\,)$	Probability density function
$p_{\max}(x, N)$	Probability density of the maximum value of x among N products
δ	The Dirac delta function
r_d	The distance from the system condition to $X_{\max}$
r_h	The distance from the system condition to H if there is any failure, Or to $X_{\max}$ if there is no failure
r_t	The distance from the failure time of a product to the first failure time
r_{rul}	The distance from the RUL of a product to the minimal RUL
$\rho(r, N)$	The density of states (DOS) to the maximum of a sequence of N i.i.d. random observations with distance r
ρ_d	The DOS near-extreme system condition without a failure
ρ_h	The DOS near-extreme system condition with a failure
ρ_t	The DOS near-extreme failure time
$\rho_{online\,h}(r_h)$	The online DOS near-extreme system condition
$\rho_{online\,rul}(r_{rul})$	The online DOS near-extreme RUL
$\overline{\rho(\bullet)}$	The mean DOS

Sabhapandit and Majumdar for a set of independent and identically distributed random variables [7]. The recently near-extreme method was applied to validate a financial market model for the intraday market fluctuations [8]. A generalized state density (GDOS) was proposed to analyze the stock data under near-historical extreme events [9]. The near-extreme events in Brownian motion were analyzed to estimate the amount of time spent on a near-maximum distance traveled [10]. The use of accident precursor data was integrated with hierarchical Bayesian model to estimate the risk probability of low-frequency and high-consequence events [11]. When we deal with an extreme event, it is unlikely that we can ignore the influence from these near-extreme events.

Prognostics and health management (PHM) scheme has been applied to estimate the RUL of mission critical products, such as batteries [12], operation state switches [13], turbine creep [14], bearings [15], gas turbine engines [16]. According to [17], PHM can be classified into three categories: (a) model based approaches [18,19]; (b) data-driven based approaches [20,21]; and (c) physical-of-failure based approaches. The goal of the prognostics should not only focus on extreme RUL prediction, but also the near-extreme situations. Here, we use these predictions for the assessment of a batch of products instead of just a single product [22]. In maintenance planning, group-based preventive maintenance policy has been used in production scheduling [23]. When there is a batch of products, the customers not only concern about the first failure time among these products, but also interested in the near-extreme failures. Seeking a quantitative solution to this type of problem is rather difficult due to the crowding phenomenon, especially when the worst condition is characterized by an estimated distribution function.

Particle filtering [24] has been widely applied in the community of prognostics, such as RUL of slurry pumps impellers [25], electrolytic capacitor [26], bearings [27], LED driver [28], and lithium-ion batteries [29], among others. The adaptive neuro-fuzzy system with high order particle filter was combined for machine prognosis [30]. The dynamic particle filter was used for parameter estimation in support vector regression model for reliability prediction [31]. The particle filter with a log-likelihood ratio approach was proposed to detect the failure of hybrid dynamic systems [32]. The particle filtering technique and kernel smoothing method were combined for prognosticating the health of newly designed components [33]. Therefore, particle filtering has shown to be an effective tool in prognostics and health management of aging components or systems.

The rest of this paper is organized as follows. In Section 2, the assumptions and the problem formulations are presented. In Section 3, we propose offline solutions not only for near-extreme system condition with and without a failure, but also for near-extreme failure time. In Section 4, we provide several online solutions for online diagnostics and prognostics of near-extreme system condition and near-extreme RUL in the framework of the PHM by particle filter. In Section 5, numerical examples are presented to demonstrate the effectiveness of the proposed approach. Section 6 concludes the paper.

2. Problem formulation

In this section, we introduce the background for the generation of the problems, assumptions for calculation and simplification, and definitions.

As we mentioned above, the problem exists when we intend to make reliability evaluations for a group of products with finite numbers. For example, when the first gas turbine blades in a group fails because of reliability degradation, should the remaining blades that are still functional be decommissioned under a similar working condition? In this way, we are using evaluation indicators from two basic perspectives: system condition and RUL. That is, what is the mean density of the condition to a failure threshold? In addition, what is the mean density of the RUL to the time to be decommissioned? Especially in this case, we want to avoid the failure crowding of the blade fleet. It means that they hope that the phenomenon of the failure crowding should not occur. For another example, there is a system composed of several identical parts working in series with a spare part for emergency. If one component fails, it can be replaced by the spare part. However, when failures of components happen in a crowding way, we must allocate and stock more spare parts. In order to analyze this type of failure mechanism, we propose the near-extreme condition and near-extreme RUL to solve the problem.

Here we state the assumptions for a group of products:

- Degradation. Every product deteriorates with a monotonically increasing degradation process. The damages of products at each time step are accumulative. We assume degradation is the main factor leading to the failure, such as fatigue, aging, wear, and other types of accumulative damage. Hence, continuous stochastic processes are used to model and degradation process.
- Similarity. The finite number of products are operating in a similar working condition from the same batch or similar producing processes. For the same group of products, the degradation follows the same stochastic process. Moreover, the degradation processes are independent with each other, while weak correlations are allowed among themselves. The operation environment of N products are similar to each other, then they share the same distribution of degradation state at time t.
- Failure. A failure occurs if the degradation exceeds the failure threshold, which is predefined constant value. Although the degradation processes are independent among these products, the failure threshold is the same for all degradation processes. When there is no failure, there is only one product with the maximum value of degradation state. The remaining useful time is from the time to predict to the time to failure.
- Finite number. Here we only consider a group of identical products with finite number. Therefore, it is not appropriate to use the normal